

**MODELING THE EVOLUTIONARY HISTORY OF THE SOLAR NEBULA.** T. F. Stepinski, *Lunar and Planetary Institute, 3600 Bay Area Blvd., Houston TX 77058, USA.*

**Abstract.** According to the current concepts, the solar nebula was an active and changing environment. It appears that it is the evolutionary aspect of the nebula that shapes the global character of the solar system. Thus, the solar system origin studies require a evolutionary model of the nebula. To address this situation we have constructed an analytic model of the evolving solar nebula based on the same set of physical principles used in numerical time-dependent models of protoplanetary disks. Final formulas are explicit and readily available to provide the structure of the gaseous solar nebula on demand. The analytic model is conceptually transparent, thus, in comparison with its numerical counterparts, it gives much deeper insights into the inner working of the evolving nebula. It also provides an “easy-to-use,” but physically solid, theoretical framework within which numerous “origins” issues can be discussed.

**Introduction.** The observations of protoplanetary disks surrounding T Tauri stars (Beckwith 1994) support the view of an active, ever-changing disk of a limited life-span. If observable T Tauri stars are indeed look-alikes of our Sun progenitor, then it is probably more appropriate to think about the solar nebula as a process instead of an object. The theoretical foundation upon which such a process can be studied is a time-dependent accretion disk theory. Numerical models of the solar nebula based on this concept has been constructed (see, for example, Ruden and Pollack, 1991), but they have two major shortcomings. (1) They are not readily available as modules in further studies because they require time-consuming calculations to yield a single result. (2) By producing a single result at the time, the numerical solution fails to unveil the overall structure of the process. To address these problems we have constructed an analytic model of the solar nebula based on a time-dependent accretion disk theory. Our model incorporates the same physical processes as the numerical model of Ruden and Pollack (1991), but it yields the final results in the form of explicit, analytic formulas, and, unlike the numerical model, it can be readily employed in many “origins” calculations.

The short format of this paper precludes the full presentation of our model, instead we describe its basic design, present some examples, and discuss potential applications.

**The analytic model.** To calculate the physical properties of the nebula, we solve the standard, thin disk set of equations (see, for example, Reyes-Ruiz & Stepinski, 1995). The problem consist of solving several algebraic equations and one partial differential nonlinear diffusion equation. The major problem in applying the standard disk formalism to the solar nebula is the complicated form of the opacity. For the temperature and density regimes appropriate to the solar nebula the opacity is dominated by dust grains. However, as the temperature and the density change with the distance from the Sun, different opacity regimes set at different regions of the nebula. Moreover, as the nebula cools down, the radial locations

of opacity regimes change. In our model we consider three different opacity regimes, the ice grains opacity regime, the ice grains sublimate opacity regime, and the silicon and iron grains opacity regime. Within the ice grains opacity regime we distinguish between optically thick nebula and marginally optically thick nebula. Overall, the opacity is given by the piecewise-continuous power-law formulas. Using the algebraic equations we can derive power-law formulas for viscosity,  $\nu = \nu(r, \Sigma)$ , as functions of the distance from the Sun and the surface density. Next, we use the self-similar approach to find the distribution of the surface density without actually solving the diffusion equation. The time dependence of  $\Sigma$  is given parametrically, in terms of the scaling factor which we chose to coincide with the outer radius of the nebula. The time dependence of the scaling factor is found separately, so the actual time dependence of  $\Sigma$  can be established.

The model has three important parameters, initial mass of the nebula,  $m_{d0}$ , initial angular momentum of the nebula,  $j$ , which remains unchanged during the evolution, and the viscosity parameter  $\alpha$ . We have found that the evolution of the nebula passes through different epochs defined by different rates of the evolution. The connection between different viscosity regimes, which are separated radially, and different epochs, which are separated in time, can be understood as follows. There are usually two or more regimes present in the nebula at any given time, so different regions of the nebula behave locally according to their local viscosity regimes, however, there is always a dominant regime (in the first approximation, the regime which holds most of the nebula mass) which sets the overall behavior of the nebula. At different times different regimes are dominant thus giving rise to different epochs.

**Examples.** The evolutionary history of the nebula depends on the initial conditions. Figure 1. shows how two, not so different, sets of initial conditions result in different evolutionary scenarios. The first model starts from  $m_{d0} = 0.245M_{\odot}$ ,  $j = 5.6 \times 10^{52} \text{ g cm}^2 \text{ sec}^{-2}$ , and the second model starts from  $m_{d0} = 0.1M_{\odot}$ ,  $j = 4 \times 10^{52} \text{ g cm}^2 \text{ sec}^{-2}$ . In both cases  $\alpha = 0.01$ . The first model passes through four epochs, but the second model passes through only two epochs. Eventually, after  $\sim 10^5$  years the nebula finally “forgets” the initial conditions. This time can be shorter if  $\alpha$  is larger (physically, not a plausible scenario), or longer if  $\alpha$  is smaller (physically, quite plausible scenario). The time during which the nebula “remembers” the initial conditions is long in comparison with the time needed to form planetesimals. Therefore, it seems that in order to calculate the distribution of solid material circumnavigating the Sun in the form of the planetesimal swarm, the evolutionary aspect of the gaseous nebula has to be taken into account. Inasmuch as our model describes only the evolution of nebular gas and not the solids, it cannot predict the character of the solar system, but it is clear that this character depends on the initial conditions.

## Modeling the Evolutionary History of the Solar Nebula: T. F. Stepinski

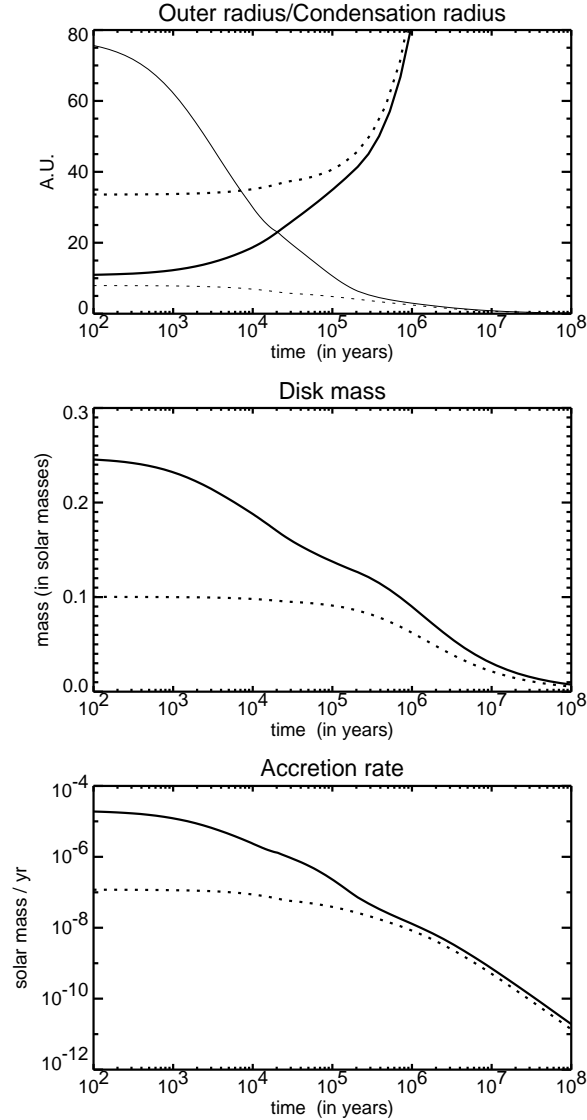


Figure 1: Summary of the solar nebula evolution. The solid lines correspond to the model characterized by  $m_{d0} = 0.245M_{\odot}$ ,  $j = 5.6 \times 10^{52} \text{ g cm}^2 \text{ sec}^{-2}$ , and  $\alpha = 0.01$ , and the dotted lines correspond to the model characterized by  $m_{d0} = 0.1M_{\odot}$ ,  $j = 4 \times 10^{52} \text{ g cm}^2 \text{ sec}^{-2}$ , and  $\alpha = 0.01$ . The lighter, decreasing lines on the uppermost figure describe the location of the water condensation front.

For example, the nebula evolving according to our second model can be considered to be approximately steady-state for the initial few  $\times 10^5$  years. The location of the water condensation front ("snow line") remains fixed at about 7-5 AU. One can speculate, that such conditions are "good" for the formation of our solar system. On the other hand, the nebula evolving according to our first model develops snow line only after about  $3 \times 10^4$  years, at the distance of about 20 AU. For the next few  $\times 10^5$  years the location of this snow line drifts inward. One can speculate that such conditions are "bad" for the formation of the solar system as we know it. Thus, it is possible that our solar system is unique in its character, and other planetary systems may be different.

**Conclusions.** We have developed an "easy-to-use" evolutionary model of the solar nebula. Our model can be, in principle, tested against the observed properties of protoplanetary disks in T Tauri stars. It yields a definitive disk mass – disk accretion rate relationship which can also be obtained from observational data. We have shown that the history of the nebula depends strongly on the initial conditions at the onset of the viscous stage. It remains to be seen whether these conditions are narrowly or broadly defined by processes prior to the viscous stage. If the broad range of initial conditions is possible, planetary systems of different designs are conceivable.

Several ongoing "origin" investigations can benefit from our model. (1) The issue of the solar nebula dispersion. As can be seen from Figure 1, the viscous stress alone can remove most of the gas. This is because we have assumed a constant  $\alpha$  model following an argument that different nebula drivers operate at different times to provide viscosity throughout the nebula life-span. For example, the nebula can be initially driven by convection, but later, when the surface density drops and the degree of ionization due to cosmic rays increases, it can be driven by the magnetorotational instability. (2) Global evolution of solids, a key to understanding the character of the solar system, requires the gas evolution component. Existing calculations address this issue by using a numerical gas evolution model, but the analytic model can speed up the calculation. (3) Planet migration requires the knowledge of the gas distribution. Existing calculations use the antique "minimum mass" model, and can be placed on much more solid theoretical framework by using the time-dependent model. (4) Modeling properties of chondritic meteorites. Using our model one can calculate the radial distribution of elements. This can be compared with the abundances of elements in chondritic meteorites. This way we could understand, from first principles, whether the elemental fractionation occurred by condensation or by a more complicated process.

## References

1. Beckwith, S.V.W. 1994 in *Theory of Accretion Disks* -2 ed. W.J. Duschl, J. Frank, F. Meyer-Hofmeister & W.M. Tscharnuter (Kulwer Academic Publishers), 1.
2. Ruden, S.P., Pollack, J.B. 1991, *ApJ*, 375, 740.
3. Reyes-Ruiz, M., Stepinski, T.F. 1995, *ApJ*, 438, 750.